

Arguments against a dominantly hadronic origin of the VHE radiation from the supernova remnant RX J1713-3946

R. Plaga
Franzstr. 40, 53111 Bonn, Germany*

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Abstract

The flux of photons above 1 TeV from the direction of the centre and a cloud in the western part of the nearby southern supernova remnant (SNR) RX J1713.7-3946 is calculated in the “hadronic scenario” that aims to explain the intense VHE radiation from this remnant with the decay of π_0 pions produced in nuclear collisions. The expected flux from its centre is found to fall short by about factor 40 from the one observed by the HESS collaboration. This discrepancy presents a serious obstacle to the “hadronic scenario”. The theoretically expected flux from the molecular cloud exceeds the one observed by HESS by at least a factor 3. While the size of this discrepancy might still seem acceptable in the face of various theoretical uncertainties, the result strongly suggests a strict spatial correlation of the cloud with an excess of TeV γ radiation. The observational lack of such correlations in the remnant reported by HESS is another counter argument against the hadronic scenario. In combination these arguments cannot be refuted by choosing certain parameters for the total energy or acceleration efficiency of the SNR.

1 Introduction

The nearby supernova remnant (SNR) RX J1713.7-3946 is a brighter source of TeV photons than any SNR in the northern sky and, together with the SNR RX J0852.0-4622, may well be the VHE brightest SNR in the entire sky (Aharonian et al., 2005). Two alternative scenarios were proposed for the dominant origin of the TeV radiation from this source by Aharonian et al.(2005)¹. In the *electronic scenario* it is due to inverse Compton scattering of energetic electrons mainly

*E-mail address: rainer.plaga@gmx.de

¹ Aharonian et al. (2005) argue that “mixed” scenarios, in which both electrons and protons contribute to a major part of the total emission seem unlikely because they require fine tuning of some parameters.

on photons of the microwave background radiation. In the *hadronic scenario* it is due to the decay of neutral pions that were produced in collisions of energetic protons gas ambient to the remnant. Conclusive evidence for the latter scenario would be of momentous importance for the theory of cosmic-ray origin, because it would constitute the first direct evidence for the acceleration of protons in SNRs. However, it is my purpose here to present two serious problems with a hadronic scenario for RX J1713.7-3946.

2 The basic argument

RX J1713.7-3946 is probably the remnant of a supernova in A.D. 393 at a distance $D \approx 1$ kpc (Cassam-Chenai et al., 2004). Presently it has a very roughly spherical shape with a radius $r_{\text{SNR}} \approx 0.5^\circ$ (8.6 pc). While it mostly expands into a void that was probably blown by the wind of the supernova progenitor, it has recently hit a complex of molecular clouds in its western part. In this direction the ambient density has been measured to be about $300/\text{cm}^3$, while in the centre the ambient density has been observationally constrained to $< 0.02/\text{cm}^3$ (Cassam-Chenai et al., 2004)². In the hadronic scenario the TeV emissivity within a cosmic-ray accelerator is directly proportional to the amount of ambient “target material” (Aharonian et al., 1994). As most of the baryonic matter within RX J1713.7-3946 is clumped, the emissivity is then expected to be strong in the direction of the molecular clouds in the western part of the remnant and quite weak near the remnant’s centre. Yet, observations find a flux from its centre that is only slightly weaker than the one from the western region. Further there is no apparent spatial correlation of the flux with the molecular clouds (Aharonian et al., 2005). These discrepancies between theoretical expectation and observation constitute my basic arguments against a hadronic origin of the VHE radiation from RX J1713.7-3946. In the following they are refined and quantified, in the latter case for the example of one well studied molecular cloud.

²Recently it has been claimed that this upper limit can be avoided by assuming an extremely low electron temperature below 0.1 keV in the remnant, due to efficient particle acceleration (Takahashi et al., 2007). However, the measurements of Cassam-Chenai et al. (2004) find an electron temperature of about 0.6 keV in the central region of RX J1713-3946 (with low statistical significance). Moreover, temperatures below 0.1 keV have not been found in any young SNR. The remnants with a claimed evidence for an “acceleration cooling effect” all have electron temperatures above 0.4 keV (Decourchelle et al., 2000).

3 Predictions for the VHE flux from π_0 decay

3.1 General parameterization

I use a simple parameterization of Aharonian et al. (1994) to predict the integral flux of γ -rays above an energy E :

$$F(\geq E) \approx 9 \cdot 10^{-12} \left(\frac{\theta}{0.1} \right) \left(\frac{E}{1 \text{ TeV}} \right)^{-1.1} \left(\frac{E_{\text{SN}}}{10^{51} \text{ erg}} \right) \left(\frac{D}{1 \text{ kpc}} \right)^{-2} \left(\frac{n}{1 \text{ cm}^{-3}} \right) \text{ cm}^{-2} \text{ sec}^{-1}. \quad (1)$$

Here θ is the fraction of the supernova explosion energy E_{SN} that has been converted to cosmic rays with a power-law spectrum up to energies much larger than E with an index of -2.1³. I choose the standard value for θ , derived from a requirement that SNRs are the main source of Galactic cosmic rays (Gaisser, 1990). I will come back to the question if a different value might be chosen in the concluding section 4. D is the distance to the remnant and n is the ambient density of baryonic matter within the source. This rough treatment is not expected to yield predictions with a precision of better than 10 %. Therefore the inclusion of effects with a small effect on the integral flux above 1 TeV, like e.g. the high-energy cutoff of the observed spectrum (Aharonian et al., 2007) have been neglected.

3.2 VHE radiation from the centre of the remnant

The centre of the remnant contains no molecular clouds. Because a strong shock must have passed and strongly heated this area, the upper limit on the ambient gas density from the absence of thermal X-ray radiation (Cassam-Chenai et al., 2004) is generally thought to be reliable in this region. On this basis, an upper limit on the integral flux above 1 TeV from the centre of RX J1713.7-3946 within the “resolution radius” of $r_S \approx 4.8'$ for the HESS measurements (that contains 68 % of all events from a point source) is given by:

$$F_{\text{theory-centre}}(\geq 1 \text{ TeV}) \leq 7 \cdot 10^{-15} \left(\frac{\theta}{0.1} \right) \left(\frac{E_{\text{SN}}}{10^{51} \text{ erg}} \right) \left(\frac{D}{1 \text{ kpc}} \right)^{-2} \left(\frac{n}{0.02 \text{ cm}^{-3}} \right) \left(\frac{r_{\text{SNR}}/r_S}{6.3} \right)^{-2} \text{ cm}^{-2} \text{ sec}^{-1} \quad (2)$$

This equation is derived from eq.(1) by multiplying it with the last factor that specifies the relative solid angle of the central region relative to the total solid angle of the remnant. From fig.2 and table 2 of the recent publication of deep HESS observations of RX J1713.7-3946 (Aharonian et al., 2007) I find for the observed integral flux above 1 TeV from the direction of the centre of the remnant

³This index is expected theoretically and agrees with the index of the TeV spectrum of RX J1713.7-3946 within the errors up to an exponential cutoff at about 20 TeV (Aharonian et al., 2005)

within a resolution radius:

$$F_{\text{observed-centre}}(\geq 1\text{TeV}) \approx 2.9 \cdot 10^{-13} \text{cm}^{-2} \text{sec}^{-1} \quad (3)$$

The observed flux is larger by a factor of more than 40 than the upper limit on the theoretically expected from π_0 decay. A hadronic origin of this radiation is improbable on the basis of this discrepancy alone.

3.3 VHE radiation from the direction of “cloud C”

Based on deep observations of RX J1713.7-3946 in the mm-wave and X-ray spectral region with various radio and X-ray telescopes it is generally thought that the shock wave of the remnant recently ran into a complex of molecular clouds, identified by their CO emission and optical absorption, in its western part (Cassam-Chenai et al., 2004; Hiraga et al., 2005). The four major identified CO peaks (labelled “A-D” by Fukui et al.(2003)) are all located on top of prominent X-ray features, suggesting that the dense molecular gas is being impacted by blast waves and its surface becomes bright in X-ray emission (Fukui et al., 2003). Shock waves slow down fast and the cooling time scale can become very short within dense clouds. Therefore the upper limits on the ambient density from the absence of thermal X-ray radiation do not apply for this region of the remnant (Cassam-Chenai et al., 2004).

“Cloud C” is an isolated molecular cloud, well within the south-western rim of the remnant (Fukui et al., 2003). Its radius is about $r_c=3'$ (0.9) and I idealize it as spherical. Its coincidence with a region of enhanced X-ray brightness and a broad-line component of CO emission are strong observational indications that this cloud has interacted with the shock wave of RX J1713.7-3946 (Hiraga et al., 2005). Both an absorption of X-ray spectra in the SW part of the remnant and the intensity of the CO line allow to derive an additional absorption column density at the position of the cloud of about $N_H=6 \cdot 10^{21} \text{cm}^{-2}$ (from fig. 4 of Cassam-Chenai et al. (2004) and fig.2 of Fukui et al. (2003), respectively). This translates to an ambient density within cloud C of about $n = N_H/(2 r_c) \approx 1100/\text{cm}^3$. The mass of cloud C is thus about $70 M_\odot$. The expected integral flux above 1 TeV from the direction of the cloud within the resolution radius of $4.8'$ is then expected to be:

$$F(\geq E)_{\text{theory-cloud}} = 1.4 \cdot 10^{-12} \left(\frac{\theta}{0.1} \right) \left(\frac{E}{1\text{TeV}} \right)^{-1.1} \left(\frac{E_{\text{SN}}}{10^{51}\text{erg}} \right) \left(\frac{D}{1\text{kpc}} \right)^{-2} \left(\frac{n}{1100\text{cm}^{-3}} \right) \left(\frac{i}{1/5} \right) \left(\frac{(r_{\text{SNR}}/r_c)}{10} \right)^{-3} \text{cm}^{-2} \text{sec}^{-1} \quad (4)$$

This equation is a generalization of eq.(1) to estimate the expected flux of γ rays from a molecular cloud interacting with the SNR. The last factor takes into account that if the cosmic-ray density within the cloud is the same as within the rest of the remnant (“full immersion”) the total fraction of cosmic rays interacting with the cloud is the volume fraction of the cloud relative to the

total remnant. The factor “i” is an “immersion factor” that parameterizes the volume fraction of the cloud that is immersed in the mean hadronic cosmic-ray density within the remnant. It is difficult to determine i because the diffusion coefficient for cosmic rays within the remnant is poorly known. In the following I try to obtain a conservative *lower limit* on i.

I assume that cosmic-rays are not accelerated within the dense cloud, due to a slower shock speed. The entry into and propagation within the cloud is assumed to be diffusive. This assumption seems justified by observational evidence that the turbulent and magnetic energy density are practically equal within molecular clouds (Crutcher, 1999). The diffusion coefficient $D_{\text{intercloud}}$ of cosmic rays within the cloud is estimated to have the standard interstellar value (Gaisser, 1990) scaled with the ratio r of interstellar to intercloud magnetic field strength. Assuming $r \approx 10$ for cloud C (Crutcher, 1999) I find $D_{\text{intercloud}} \approx 5 \times 10^{29} \text{ cm}^2/\text{sec}$ at an energy of 10 TeV. I conservatively neglect diffusion into the cloud from within the remnant and assume that the diffusion of protons and nuclei into the cloud takes place exclusively from the region upstream of the shock, the *precursor*. Within the precursor I assume Bohm diffusion with a magnetic field of $3 \mu\text{G}$ i.e. a diffusion constant $D_p = c r_L/3$ where r_L is the Larmor radius. The measured spectrum from RX 1713.7-3946 shows a highly significant exponential cutoff at an energy $E_{\text{max}} \approx 20 \text{ TeV}$ (Aharonian et al., 2007). My estimate for D_p yields a maximum proton (or electron) energy $E_{\text{max}} \approx 50 \text{ TeV}$ within the standard theory of shock-wave acceleration (Gaisser, 1990)⁴. This value is similar to the observed value of the exponential cutoff of the spectrum, thus confirming the consistency of my parameter choices. I assume a precursor width of $l_{\text{CR}} \approx D_p/v_s$ (Malkov et al., 2005) and a time period t_p during which the particles diffuse into the cloud of $t_p = l_{\text{CR}}/v_s$.

The diffusion coefficient in the precursor $D_p \approx 2 \times 10^{26} \text{ cm}^2/\text{sec}$ is about a factor 5000 smaller than the one in the cloud $D_{\text{intercloud}}$. We therefore assume that the diffusion into the cloud is limited by the replenishment of cosmic rays from the precursor which is determined by D_p . A depth of extraction x_p of ambient cosmic rays with an energy E from the precursor into the cloud is calculated by the plane source solution Fick’s law (Gaisser, 1990). D_p and t_p are then expressed by the expressions explained in the present paragraph and one obtains:

$$x_p > \sqrt{D_p t_p} = 0.06 \text{ pc} \left(\frac{E}{10 \text{ TeV}} \right) \left(\frac{v_s}{5000 \text{ km/sec}} \right)^{-1} \quad (5)$$

A lower limit on “immersion factor” is then given as:

$$i > \left(\frac{r_c + x_p}{r_c} \right)^3 - 1 \approx 1/5 \quad (6)$$

for $r_c \approx 0.9 \text{ pc}$ and $x_p \approx 0.06 \text{ pc}$.

From fig.2 and table 2 of the recent publication of deep HESS observations of RX J1713.7-3946 (Aharonian et al., 2007) I find for the observed integral flux

⁴ An acceleration time of 1600 years and a shock speed $v_s \approx 5000 \text{ km/sec}$ were assumed.

above 1 TeV from the direction of cloud C within a radius of $4.8'$ (within which 68 % of all events from the cloud are expected (Aharonian et al., 2005)) ⁵:

$$F_{\text{observed-cloud}}(\geq 1\text{TeV}) \approx 5 \cdot 10^{-13} \text{cm}^{-2} \text{sec}^{-1} \quad (7)$$

The theoretical *lower* limit (eq. (4)) *exceeds* the observed value (eq. (7)) by about a factor 3. This predicted flux would have made cloud C the brightest TeV feature in RX J1713.7-3946 by far (about a factor 2 brighter than the its brightest TeV feature in the NW of the remnant). With other words: even under extremely conservative assumptions about acceleration within and diffusion into molecular clouds overtaken by a supernova blast waves, cloud C should be a very prominent and (for the HESS experiment) effectively *point-like* feature if the VHE radiation were of hadronic origin. While a discrepancy of a factor 3 might still be acceptable in the face of various theoretical uncertainties, the prediction of a point-like excess from cloud C with the hadronic model seems robust.

Contrary to this expectation the HESS collaboration found “no apparent correlation between CO intensity and the HESS gamma-ray excess” (quote from a collaboration member (Funk, 2007)) in general, and (in fig.17 in Aharonian et al.(2005)) no VHE excess at the position of cloud C (located at an azimuth of $\approx 170^\circ$) in particular.

4 Conclusion

There are strict upper limits on thermal X-ray radiation from the SNR RX J1713.7-3946 from observations of several satellites. In the centre of the remnant these limits translate into restrictive upper limits on gas density. I argued that there is a factor 40 too little baryonic matter in its centre to explain the observed TeV radiation with hadronic processes if RX J1713-3946 is a typical accelerator of Galactic cosmic rays. ($\theta \approx 0.1$).

In principle there is more than enough matter for this feat in the western part of the SNR. However, in order to avoid the strict upper limits on thermal X-ray radiation this gas must be clumped in dense molecular clouds, and exactly this is found from the spatial distribution of CO. One would then expect that the TeV radiation is emitted mainly from the direction of the clouds and again this is in contradiction with observation.

The two problems cannot both be solved by postulating a different acceleration efficiency θ or supernova explosion energy E_{SN} : increasing either of these factors helps with the “centre problem” but aggravates the “cloud problem” and vice versa. The discrepancy further worsens if the cosmic-ray density should be higher at the remnant’s rim than at its centre, as might be expected in the hadronic scenario. These considerations practically rule out a mainly hadronic origin of the VHE radiation from RX J1713.7-3946. This conclusion is in disagreement with the one from Berezhko & Völk (2006) who argue that the observed high energy γ -ray emission can be mainly of hadronic origin. However,

⁵This approximates cloud C as an effective point source for the HESS observatory.

these authors do not take advantage of the valuable morphological information that second generation Cerenkov arrays like HESS and the X-ray satellites provide with high angular resolution. I base my arguments on exactly this information.

The “striking correlation between the X-ray and the gamma-ray image” (quote from Aharonian et al. (2005))) is evidence in favour of a leptonic origin of the radiation from RX J1713-3946. No model-independent argument has been brought forward against it, yet. The (relatively minor, i.e. smaller than a factor 2) disagreements between the “electronic scenario” of Aharonian et al. (2005) and observations could be due to idealizations they employ. The observational data in the X-ray and VHE spectral region can be explained as purely of leptonic origin in the following manner. The intensity in the X-ray and VHE spectral region correlates quantitatively nearly perfectly throughout the SNR (see e.g. fig. 16 in (Aharonian et al., 2005)). The spectral properties are the same everywhere within the measurement error in the VHE region (see fig.14 in (Aharonian et al., 2005)) and X-ray region (see table 2 in (Hiraga et. al, 2005)⁶). Porter et al. (2006) have proposed an energy distribution for an electron population, a magnetic-field strength and a detailed radiation-field energy distribution that is shown to reproduce the observed total spectrum from the radio up to the highest energies reasonably well. The simple assumptions that the magnetic field and radiation-field energy distribution are the same throughout the remnant and that the density of the electron population correlates with the X-ray intensity will then be in satisfactory agreement with all data in the X-ray and VHE region. While this model is probably too simplistic, it serves to demonstrate that the radiation from RX J1713-3946 might well be of purely leptonic origin.

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References

- Aharonian, F.A., Drury, L.O’C., Voelk, G., 1994, A&A 285, 645.
- Aharonian, F., et al., 2005, A&A 449, 223.
- Aharonian, F., et al., 2007, A&A 464, 235.
- Berezhko, E.G., Völk, H.J., 2006, A&A 451, 981.
- Cassam-Chenai, G., Decourchelle, A., Ballet, J. et al., 2004, A&A 427,199.
- Crutcher, R.M., 1999, ApJ 520, 706.
- Decourchelle, A., Ellison, D., Ballet, J., 2000, ApJ 543, L57.

⁶Cassam-Chenai et al. (2004) find a weak correlation between spectral hardness and intensity.

- Fukui, Y., Moriguchi, Y., Tamura, K. et al., 2003, PASJ 55, L61.
- Funk, S., 2007, astro-ph/0701471; Advances in Space Research (Proceedings COSPAR 2006), in print.
- Gaissler, T.K., *Cosmic Rays and Particle Physics*, (Cambridge University Press, New York, 1990).
- Hiraga, J.S. et al., 2005, A&A 431, 953.
- Malkov, M.A., Diamond P.H., Sagdeev, R.Z., 2005, ApJ 624, L37.
- Porter, T.A., Moskalenko I.V., Strong A.W., ApJ 648, L29.
- Takahashi, T. et al., 2007, preprint astro-ph/0708.2002.